Participation of an electric vehicle fleet to primary frequency control in France

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Abstract: Using electric vehicles (EV) as distributed storage units could be a solution to take advantage of the good availability of EVs and reduce their total cost of ownership. The scientific literature features frequency control as one of the most profitable electric market for EV fleets. This paper presents an economic evaluation of the expected remuneration for a fleet of EVs participating to primary frequency control in France in 2020. First, the modeling of a French EV fleet is addressed. Simulations of the participation of this fleet to the French primary frequency control market are then performed. Two regulation strategies are considered: in the first one, only unidirectional power exchanges are allowed between EVs and the grid, while in the second one bidirectional exchanges are allowed. Results show that the expected remuneration is highly dependent on the ability to charge at work, the power level of the charging stations, and the bidirectional capabilities of the cars.

Keywords: Electric Vehicles; Vehicle-to-Grid; Frequency Control; Demand Side Response; Economics; Smart Grids

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1 Introduction

The electric vehicle (EV) market seems to have reached a tipping point. On the one hand, EV sales are fostered by strong incentives, offered by governments or local authorities in order to cope with the objectives of reductions of tailpipe emissions. According to many government and agencies forecasts, the EV market is expected to takeoff and EV sales to rocket up within the next few years. On the other hand, traction battery prices are still very high (roughly 400€/kWh (International Energy Agency, 2013a)), what impacts strongly the total cost of ownership (TCO) of EVs. Moreover, the driving range hardly exceeds 200km for a full-electric vehicle. These two issues turn up to be substantial barriers to the EV development. So far, the cons have outweighed the pros, and global EV sales are not increasing as expected.

As a consequence, researchers and car automakers are investigating ways of lowering the TCO of EVs. One solution considered in the literature is to use EV batteries as distributed storage systems for the electrical grid when EVs are plugged-in. This solution is possible for two main reasons.

First, because vehicles are idle most of the time, and the average commuting trip would not empty the battery (Pearre et al., 2011). Thus, for a given EV, there would be a significant period during which the vehicle would not need to charge at full rate, and could therefore be used as a storage system from the electrical grid perspective. Furthermore, even if one single EV may be unpredictable, EV fleets would be statistically reliable.

Second, because the need for electrical storage is increasingly important. Electricity is very difficult to store, and therefore the balance between supply and demand must be managed at each moment. However, it is more and more difficult for transmission system operators (TSOs) to ensure this balance, because of the growing penetration of intermittent renewable energy sources. Electrical storage units could deal with this issue by leveling the irregular production from wind and solar sources. Moreover, the electricity share in the world final energy consumption has significantly increased during the last 40 years, from 9.4% in 1973 to 17.7% in 2011 (International Energy Agency, 2013b).

In order to capture this value, EV fleets could operate in electric markets. Several technical solutions are possible: maximization of the integration of renewable energy sources (Kempton and Tomić, 2005b; Budischak et al., 2013; Pecas Lopes and Rocha Almeida, 2009), minimization of the total fleet charging costs by benefiting from market price variations (Peterson et al., 2010b; Hoke et al., 2011; Sortomme and El-Sharkawi, 2012), controlling grid voltage (Clement-Nyns et al., 2011) and controlling frequency (Han et al., 2010; Sortomme and El-Sharkawi, 2012; Kamboj et al., 2011; Dallinger et al., 2011).

EVs have rather small-sized batteries in comparison with traditional electrical grid units, but they are able to modulate their charging rate very quickly. As a consequence, Kempton and Tomić (2005a) demonstrate that the most profitable electrical markets for EVs are those requiring little amount of energy, but quick responsiveness, and those for which remuneration is based on availability (in €/MW) and not utilization (in €/MWh). Thus, frequency control markets, given their characteristics (see section 2), appear to be the most profitable markets for EVs. However, results of previous work dealing with this issue are very different from one to another. For instance, Kempton and Tomić (2005a) come up with 1900€ a year, whereas Petit and Perez (2013) find a remuneration of only a hundred euros a year, or Han et al. (2012) who calculate up to 21200€ revenues for the entire battery life (say, 8-10 years). These differences in terms of results can be accounted for by model sensitivities to the date and the geographic location considered, to the fleet model used, and to any other simulation hypothesis.

The aim of this paper is to provide an economic evaluation of the possible earnings for an EV fleet participating to primary frequency control in France in 2020, and to put these results in perspective with those previously evoked. Two control strategies are compared. The first one only allows unidirectional power flows from the grid to the vehicles. The second one allows bidirectional power exchanges between the EVs and the grid. The fleet modeling is based on the expected French fleet in 2020.

The outline of the paper is the following. Section 2 reminds the basics of frequency control, and details our hypothesis regarding the primary frequency control market in France in 2020. Then, our fleet model is presented in section 3. Algorithms and simulation parameters are detailed in section 4. Eventually, section 5 provides the results and section 6 is the conclusion.

2 Frequency Control

2.1 The basics of frequency control

Frequency is a common characteristic within an interconnected network; at any node of the grid, the frequency value is the same (conversely to voltage, which is different from one node to another). The frequency value fluctuates around its nominal value at each moment (50Hz in Europe). However, maintaining the frequency close to its rated value is important, because most of materials have been optimized to operate at this frequency value, and devices with magnetic materials may come out of their linear range. The agents responsible for controlling the frequency value are the local Transmission System Operators (TSOs), which operate high-voltage transmission lines.

The frequency reflects the real time balance between supply and demand. If electricity generation exceeds electricity consumption, the frequency will rise above its rated value and vice versa. Consequently, TSOs manage the frequency by implementing several control levels that balance production and demand in real time.

Even if TSOs have their own rules and regulations, they basically implement three similar control levels to monitor the frequency.

The *primary control*, sometimes referred to as *frequency reserves*, is an automatic control activated instantaneously. All the TSOs that are part of the interconnected grid participate to this control when a frequency deviation occurs. The aim of this control is to stop the frequency deviation, but it will not restore the frequency to its pre-disturbance value. Resources that are part of the primary reserve are to measure the frequency locally, and to respond accordingly. Power plants or other traditional units have been providing this service for years, mainly by implementing speed control loops on their motor shaft.

The *secondary control*, or so-called *frequency regulation*, is an automatic control performed only by the local TSO where the frequency disturbance occurred. The latter implements a PI loop with a characteristic time of 30 seconds, and sends a correction signal to all the units that are part of the secondary reserve. This control restores the frequency to its rated value.

The *tertiary control* is a manual control whose objective is to support primary and secondary controls. It has a response time of 15-30 minutes.

For more details on frequency control, the authors refer to (Rebours et al., 2007b,a). In the followings, we will only focus on the French primary control.

2.2 Primary frequency control in France: actual operating principles & modeling

French primary reserve amounts to approximately 700MW. Production units that are willing to be part of primary reserves have to abide by the following rules. For any frequency deviation between -200mHz and +200mHz, the frequency droop K_i of the ith unit specifies the required power deviation according to the formula 1:

$$P_i - P_{i_0} = \min(P_{primary\ reserve}; K_i(f - f_0)) \tag{1}$$

with P_i, P_{i_0} and $P_{primary\ reserve}$ respectively the total power output, the operational power setpoint and the power reserve of the ith unit. If the frequency deviation exceeds $\pm 200mHz$, the entire reserve should be released. Figure 1 presents the power-frequency curve of a traditional unit.

In addition to these rules, units also have to abide by the following requirements (Union for the Co-ordination of Transmission of Electricity, 2004):

- Units should be able to release half of their reserve in 15 seconds, and all of it in 30 seconds
- frequency measurement accuracy should be better than 10mHz
- a dead-band of 20mHz is allowed
- frequency measurement period must be between 0.1 and 1 second

Each day, the French TSO RTE assigns a reserve capacity to all the primary reserve units, which have to respond according to the previous rules. In return, they are remunerated based on a fixed tariff amounting to 8.48€/MW (Reseaux de Transport d'Electricite, 2011).

Historically, this control has been performed by traditional power plants, which all belonged to the same company (EDF). Therefore, these rules are particularly adapted for

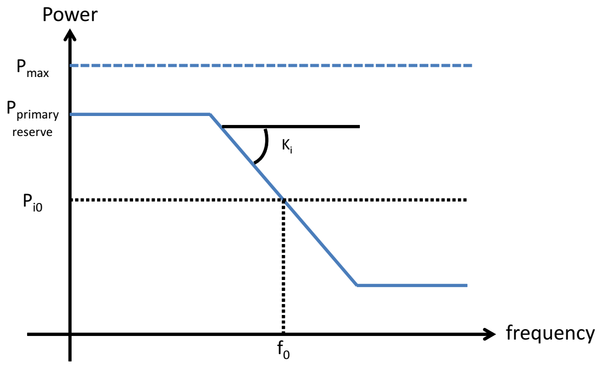

Figure 1 Power-frequency curve for a traditional unit

such units, but much less for distributed storage units. Some other TSOs, which have engaged major changes in their rules, are much more favorable for storage units (Codani et al., 2014).

We assume that RTE regulation will have changed by 2020. Indeed, the new ENTSOE (the association for TSOs in Europe) network codes, which are currently being certified and should come into force within the next few years, foreshadow future changes. First of all, frequency control will have to be organized via an auction market (European Network of Transmission System Operators for Electricity, 2013a). A demand side response (DSR) framework well suited for fast-respondent units and controllable loads is cited by the European Network of Transmission System Operators for Electricity (2012).

As a consequence, based on previous TSO surveys led by the authors (Codani et al., 2014) and considering that we target 2020, we assume that the French primary control is organized in an hourly auction market. The aggregator (see section 3.4) makes an offer (a price & a capacity in MW) for each hour. The offer granularity is supposed to be 100kW. Prices fluctuate, so we do not use the RTE fixed tariff but market clearing prices from an other European market (see section 4.2). Furthermore, we assume that EV aggregations are allowed and can participate to this market as suggested by the European Network of Transmission System Operators for Electricity (2013b). At last, the market is symmetrical, i.e. the EV fleet has to provide the same amount of power for regulation UP and regulation DOWN.

In Europe, the amount of primary reserve required is sized depending on the two biggest production units, which are unlikely to change by 2020. Moreover, Milligan et al. (2010) show that an increasing penetration of renewable energies would not necessarily result in an increase in primary reserve amount. Consequently, we assume that the French primary reserve will still amount to 700MW in 2020.

2.3 Frequency data set

Because we were not able to find publicly available frequency recordings, we used a frequency meter in order to build our own data set. We came up with 5 continuous days of frequency recordings, fully compliant with ENTSOE requirements. Figure 2 displays one hour of frequency variations (one can notice the impact of the time change from 21h to 22h).

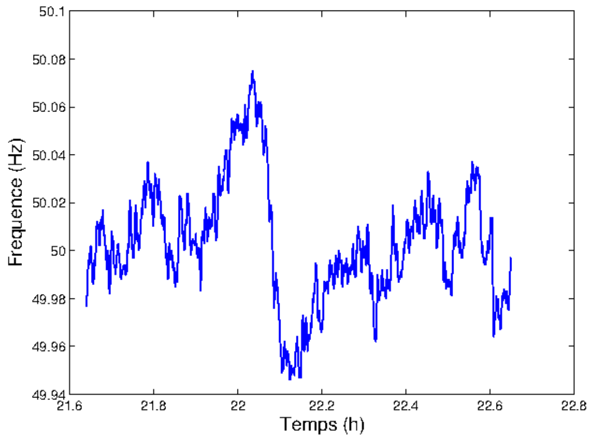

Figure 2 Frequency fluctuations over one hour, recorded at Supelec between 21h37 and 22h37 on March 28, 2014

3 Electric Vehicle fleet modeling

3.1 Electric Vehicles' characteristics

According to the International Energy Agency (2013a), the EV fleet in France should be composed of around 2 millions EVs in 2020. However, considering current EV sales, this target seems overoptimistic, and it is sure that all EV users would not be willing to join a frequency control program. As a consequence, we limit the fleet size and model a fleet of $N_{VE} =$ 200 000 EVs.

The battery size of the EVs bears little impact on the final results, and 64% of EVs had a 22kWh battery in France in 2013. Therefore, we consider that the EV fleet is consisted of EVs with a 22kWh battery. We add the constraint $0.2 < SOC/SOC_{max} < 0.9$ in order not to reach extreme SOC values, what could damage severely the battery.

3.2 Characterization of charging stations

The power level of the charging stations, or so-called electric vehicle supply equipment (EVSE), will have a significant impact on the expected fleet earnings since market remuneration is based on €/MW. As explained in section 3.3, we assume that EV uses for transportation are limited to commuting trips. Therefore, EVs can charge either at home, with their *primary EVSE*, or at work with their *secondary EVSE*. The penetration level of EVSEs at working places in 2020 remains uncertain, so we will consider four possible scenarios for this parameter. They are described in table 1.

There are four different charging levels, which are related to conventional voltage and current values: *slow charging A* (3kW, 230V, 1-phase, 16A), *slow charging B* (7kW, 230V, 1-phase, 32A), *intermediate charging* (22kW, 400V, 3-phases, 32A), *fast charging* (43kW, 400V, 3-phase, 64A – or DC charging). Table 2 presents the charging level distribution for both primary and secondary EVSEs.

Table 1 The four scenarios for secondary EVSE penetration levels

Scenarios	**Ratio of EVs having an EVSE at work**
Scenario 1	0%
Scenario 2	25%
Scenario 3	50%
Scenario 4	75%

Table 2 Breakdown of Primary and Secondary EVSEs by Charging Technology Type. Data from Prefet Vuibert (2015)

Charging level	**Primary EVSE**	**Secondary EVSE**
Slow charging A (3kW)	95%	35%
Slow charging B (7kW)	5%	34%
Intermediate charging (22kW)	0%	29%
Fast charging (43kW)	0%	2%

This distribution was deduced from a survey achieved by Prefet Vuibert (2015). Due to the high cost of charging stations, all EVSEs at home are slow chargers. Charging levels of *secondary EVSEs* are more distributed, apart from fast chargers whose penetration level stays marginal.

3.3 Electric vehicle use for transportation

EVs are first used for transportation, so we need to take into account EV trips in our model: they will have an impact on EV availabilities for frequency control (because EVs will not be plugged-in, or because they will need to charge for their next trip) and on the amount of energy remaining in EV batteries. Then, the four parameters that we need are: (a) the number of trips in a day; (b) each trip duration; (c) departure times; and (d) trip energy consumptions.

We assume that EVs are only used for the daily commuting trips, what results in two trips a day for each EV. Thus, our 5-day frequency recordings (see section 2.3) enables us to perform simulations over an entire working week.

The average daily driving distance d is taken from internal surveys from PSA Peugeot Citroen, to which we add a normal uncertainty with a standard deviation σ. We deduce the daily trip durations from these distances by using an average speed v_{ave}. This speed is also taken from PSA internal data. It is derived from average speeds on highways, on roads, in provincial urban environments and in Paris, each average speed being balanced by the percentage of trips carried out on the roads in question.

Departure times are also distributed according to normal distributions, whose means and standard deviations are arbitrarily set to fit commuting trips in the most possible realistic way.

Eventually, energy consumption is taken from the Cross-border mobility for EVs (CROME) project results. This European project, whose first goal was to demonstrate interoperability of EVSEs across France and Germany, made its data publicly available (Cross-border Mobility for EVs, 2013). We will make a distinction between a *summer type* and a *winter type* consumption, because auxiliary loads, in particular heating and air conditioning, have substantial impacts on energy consumption.

The model and parameter values for these trip data are summarized in table 3.

Table 3 Trip-related models and parameters

Trip data	**Model**	**Parameter values**
Daily trip numbers	Steady value	2
Trip distances	$d \sim \mathcal{N}(d_{data}; \sigma_d)$	d_{data} : internal use σ_d : $5km$
Departure times	$t \sim \mathcal{N}(t_{mean}; \sigma_t)$	t_{mean} : Best adapted to usual commuting trips σ_t : 2 hours
Consumption	Steady values	$c_{summer} = 129Wh/km$ $c_{winter} = 184Wh/km$

3.4 The aggregator

An EV aggregator plays the fundamental role of presenting the EV fleet as a single entity to the TSO. One single EV is very unpredictable from the grid perspective as it may leave for transportation at any moment. Furthermore, it has a very small power level on its own. An aggregator is able to deal with these issues by controlling large, statistically reliable EV fleets.

In order to do so, aggregators basically implement two algorithms: *scheduling algorithms* that are responsible for anticipating the future EV fleet conditions and bidding market offers accordingly, and *dispatch algorithms* are responsible for dispatching power flows among the different vehicles in real time. In our simulation, we do not model the scheduling algorithm, and we assume that it is fully efficient. In other words, all the aggregator capacity bids are accurate with respect to the number of EVs plugged-in, and all price bids made by the aggregator are accepted by the TSO. The dispatch algorithm implemented is described hereafter.

4 Algorithms and simulation parameters

4.1 Dispatch algorithm

The implemented dispatch algorithm mimics the one implemented in the University of Delaware demonstration project detailed by Kamboj et al. (2011). In this project, a small EV coalition participates to PJM (the local TSO) frequency regulation market, and competes in this market just as the other traditional units.

The operating principle of the algorithm, considering the market assumptions detailed in section 2.2, is the following:

1. EVs compute their preferred operating points (POP). The POP of an EV is equivalent to the operating point of a traditional unit; it represents the charging rate around which the EV will provide frequency control. Derived from the POP value, EVs calculate their power available for regulation P_{reg_i}, and communicate this value to the aggregator. The way of computing the POP depends on the bidirectional capabilities of the cars, and is presented in section 4.1.1 for bidirectional cases and in section 4.1.2 for unidirectional cases.

2. The aggregator measures the frequency. Depending on the recorded value f, and on the power bid in the market P_b (resulting from the scheduling algorithm, here assumed to be equal to the power made available by all the EVs), the aggregator computes the power to be provided for frequency control P_r:

$$P_r = \begin{cases} -\dfrac{f - f_0}{f_{max} - f_0} P_b, & |f - f_0| < 0.2Hz \\ P_b, & |f - f_0| \geq 0.2Hz \end{cases} \tag{2}$$

   with $f_0 = 50Hz$ and $f_{max} = 50.2Hz$

3. The aggregator deduces from P_r a scaling factor μ which is equal to the ratio between the power required for frequency control and the power available from EVs:

$$\mu = \frac{P_r}{\sum_{i=1}^{N_{VE}} P_{reg_i}} \tag{3}$$

4. The aggregator communicates to all the EVs their power set point for frequency control $\mu * P_{reg_i}$

5. Back to step 1 if EVs are allowed to change their POP, i.e. if $t \equiv 0 \pmod{\delta t}$, otherwise back to step 2.

Figure 3 summarizes the algorithm operating principle. This scheme is repeated for each new frequency measure, that is to say for each second. It is noticeable that there are two distinct time stamps: the first one is the frequency measurement period, bound to 1 second for safety reasons, and the second one is the POP modification period δt, defined by the market rules. As we consider an hourly market, we take $\delta t = 1$ hour.

Remark: Our algorithm is a *decentralized* one in the sense that EVs compute themselves their POP and power available for frequency control depending on their own conditions. There are *centralized* solutions, in which EVs communicate their conditions to the aggregator. The latter then decides in the name of all EVs their power available for frequency control, usually by means of an optimization algorithm. Although centralized solutions are theoretically more efficient, Vandael et al. (2013) show that both solutions tend to provide the same results. However, centralized solutions are much more time consuming, while the decentralized solution used here is implemented in a real project and proved itself to be effective.

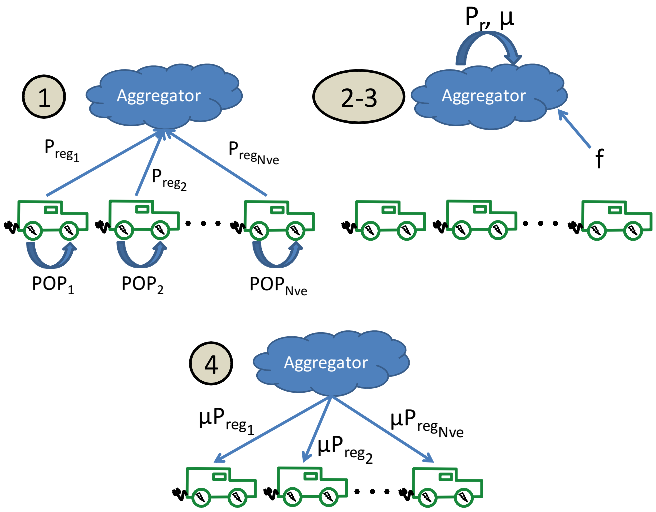

Figure 3 Dispatch algorithm operating scheme

4.1.1 Application to the bidirectional case

The way of computing the POP in the bidirectional case is also inspired from the University of Delaware solution (Kamboj et al., 2011). It takes into account the current EV conditions, and future trip needs:

$$\begin{cases} POP(t) = \frac{P_h+P_b}{2} \\ \qquad P_h = -min(P_{max}, \frac{SOC_{max}-SOC}{\delta t}) \\ \qquad P_b = min(P_{max}, \frac{SOC-E_{min}(t+\delta t)}{\delta t}) \\ P_{reg}(t) = P_{max} - \left|POP(t)\right| \end{cases} \tag{4}$$

with SOC the state of charge of the battery, $E_{min}(t)$ the energy required at time t to be able to achieve the next trip, SOC_{max} the upper SOC limit and P_{max} the power level of the EVSE.

In order to compute $E_{min}(t)$, we assume that the drivers provide the aggregator with information regarding their next trip. They communicate their next departure time precisely, and their driving range which they always approximate by their longest trip of the week (EV users are slightly subject to range anxiety).

Figure 4 presents the simulation results over 5 working days, for a bidirectional capable car (negative power values stand for charging). The primary EVSE level is 3kW, and there is no secondary EVSE. This accounts for the fact that the SOC remains steady during working periods. When parked at home, the EV participates to frequency control. When the next trip approaches, the POP increases (in absolute value) and there is less power available for regulation, then less power used for regulation. Meanwhile, the battery is charging thanks to the new POP values.

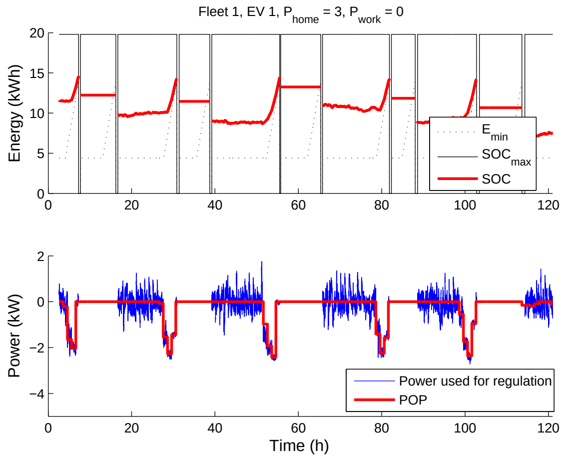

Figure 4 Simulation results for a single bidirectional capable EV over 5 working days, with $P_{home} = 3kW$ and $P_{work} = 0kW$

4.1.2 Application to the unidirectional case

In this case, the POP is computed as the steady power that enables the EV to reach the required battery SOC for next trip:

$$POP = \frac{E_r - SOC}{\Delta t} \tag{5}$$

with E_r the required energy for the next trip, SOC the state of charge and Δt the time before next departure. As the market is symmetrical, EVs necessarily need a non-null POP to be able to provide power for frequency control, and this is why this strategy was chosen.

Figure 5 presents the simulation results for one unidirectional capable car over 5 working days. The charging level at home is 3kW and 0kW at work. The impacts of having a steady POP at home are noticeable on the SOC values, as it linearly increases.

4.2 Simulation parameters

As explained in section 2.2, we aim at using market clearing prices from other TSOs rather than the fixed tariff used by RTE. We use prices from the Energinet.dk primary control market. This Danish TSO is part of the same interconnected area as RTE, but primary frequency control is organized in an hourly auction market. As for trip-related consumptions, we distinguish a *winter* and a *summer* season for prices: we use data from 2013 quarters 2 & 3 for summer prices, and data from 2012 quarter 4 and 2013 quarter 1 for winter prices. These clearing prices are available online (Energinet.dk, 2013). For each simulation, we randomly select five continuous hourly market prices from our data set.

For each EVSE penetration scenario, and for each control strategy (bidirectional or unidirectional), we perform 10 simulations with the *summer* parameters and 10 with the *winter* ones. Results are featured in the next section.

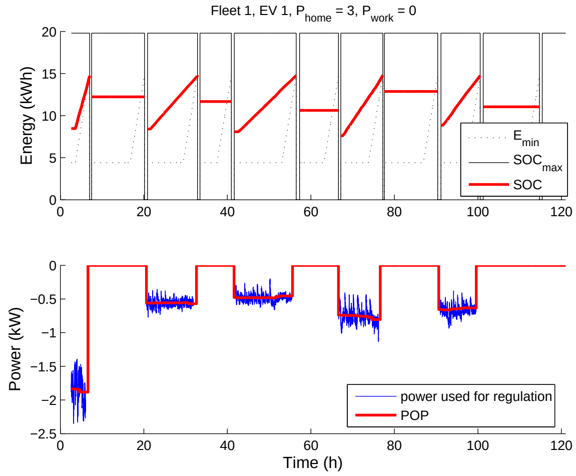

Figure 5 Simulation results for a single unidirectional capable EV over 5 working days, with $P_{home} = 3kW$ and $P_{work} = 0kW$

5 Results

This section presents our main results. Results are either per vehicle, or for a fleet of N_{VE} = 200 000 EVs.

5.1 Fleet remuneration

Average earnings per vehicle and per year are presented in table 4, for the various EVSE power levels and the two control strategies. As we performed simulations for five continuous working days, results in table 4 do not take into account week-end remunerations, so the overall yearly EV earnings may actually be higher. However, week-end driver behaviors are uncertain, and we did not have enough data to correctly model this behavior. Results from *summer* and *winter* simulations are averaged.

The expected remuneration is much higher with the bidirectional control strategy. Moreover, the unidirectional strategy can not take advantage of the possibility to charge at work, or with a higher power level. Indeed, because the market is symmetrical, the power available for frequency control is null if the POP is null too. Consequently, as the POP depends on the future driving needs, the power available for regulation is also dependent on the driving needs. On the contrary, with the bidirectional control strategy, results are very sensitive to the available power level. The expected remuneration reaches significant values for high power levels, up to 1 950€ per vehicle and per year.

These results, given the EVSE penetration at work and the EVSE distributions provided respectively in tables 1 and 2, lead to the findings summarized in table 5. We assume that the aggregator equally remunerates all the EVs, that is, the overall fleet earnings are fairly divided among the vehicles no matter their charging station power.

The expected remunerations for the unidirectional case are rather low and would probably not account for enough financial incentives for the technology to be developed.

Table 4 Average earnings per vehicle and per year depending on the EVSE power level

EVSE power level		Unidirectional strategy	Bidirectional strategy
Primary	Secondary		
3	0	25.6€	138€
3	3	42€	239€
3	7	29€	389€
3	22	26.6€	1036€
3	43	30€	1 665€
7	0	25.7€	365€
7	3	27.3€	418€
7	7	28€	600€
7	22	40.4€	1 114€
7	43	27.6€	1 950€

Table 5 Average earnings per EV and per year for each scenario.

Scenario	Unidirectional control	Bidirectional control
Scenario 1	25€	149€
Scenario 2	28€	251€
Scenario 3	29€	353€
Scenario 4	31€	456€

On the contrary, remunerations for the bidirectional case seem promising, even when the penetration of EVSEs at work is low.

5.2 *Fleet size*

Table 6 provides the hourly minimum and average power available for frequency control for the entire fleet over 5 working days. For the unidirectional strategy, the minimum is always zero because the power available for regulation is null as soon as the POP is also null.

We can put these results in perspective with the actual French primary reserve, which amounts to approximately 700MW. The question of the ideal fleet size arises: in scenario 4 with the bidirectional strategy, the reserve level is saturated in average by the EV fleet. Thus in this case, the EV fleet size is too important, since in some cases the aggregator would be required to cap its bids many times. Thus, there is no need for a very high penetration of EVs for this technology to be profitable. Conversely, too many EVs would saturate the reserve level, and at some point adding an extra EV in the fleet would result in a diminution of the earnings per EV.

Table 6 Hourly minimum P_{min} and average P_{moy} powers provided by the entire fleet of 200.000EVs

Scenarios	Unidirectional strategy		Bidirectional strategy	
	P_{min} (MW)	P_{moy} (MW)	P_{min} (MW)	P_{moy} (MW)
Scenario 1	0	102	1.6	311
Scenario 2	0	109	6.5	501
Scenario 3	0	116	11.4	692
Scenario 4	0	123	16.2	882

5.3 Limits of the survey

Our survey has two main limits. First, the battery degradation induced by the participation to frequency control has not been evaluated. Several previous studies tried to take this parameter into account (Han et al., 2012; Peterson et al., 2010a; Qian et al., 2011). Han et al. (2014) even present a battery degradation model for Vehicle-to-grid applications. However, none of these models has ever been experimentally verified, and the aforementioned surveys do not use similar methods nor find similar results. By lack of agreement on a given model or results, we decide not to model battery degradation, which is still a major issue for these technologies.

Then, we did not assess the extra cost for upgrading the power electronics to make them bidirectional capable. It is difficult to say which operator would bear these costs, between car manufacturers, car users, aggregators, charging station operators... However, they should not be too significant, as most the required power electronic devices are already present in the existing facilities.

6 Conclusion

In this work, we present an economic evaluation of the expected earnings for an EV fleet participating to primary frequency control in France. Two control strategies – unidirectional and bidirectional – are compared, with various EVSE penetration level at work. Results show that the bidirectional control outperforms by far the unidirectional one. EVSE penetration at work has also a significant impact on the overall expected remuneration. Furthermore, our results suggest that a too important EV fleet could easily saturate the reserve level: with 200 000 EVs, the entire reserve might be saturated depending on the EVSE power capabilities.

Further work could consist in taking into account battery degradation and bidirectional capable facilities upgrading costs, in order to put our results in perspective. Another lead would be to complete our EV fleet modeling, taking into account week-end behaviors and a more sophisticated model for EV departure times. Eventually, it would be interesting to perform the same kind of simulations for a non-symmetrical market. In this case, the unidirectional control strategy may perform much better.

Acknowledgement

This research benefits from the support of the Chair "PSA Peugeot Citroen Automobile: Hybrid technologies and Economy of Electromobility", so-called Armand Peugeot Chair led by Ecole CentraleSupelec and ESSEC business school and sponsored by PEUGEOT CITROEN Automobile.

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